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<td><strong>Author(s)</strong></td>
<td>Matsuda, Fukuhisa; Billy, Jozef; Takano, Genta; Nayama, Michisuke; Sakamoto, Naruo; Kuri, Shuhei</td>
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Osaka University
Effect of Welding Cooling Rate and PWHT Conditions on the Toughness of Electron Beam Weld Metal

Fukuhisa MATSUDA*, Jozef BILLY**, Genta TAKANO***, Michisuke NAYAMA***, Naruo SAKAMOTO*** and Shuhei KURI***

Abstract

Application of electron beam welding for heavy section large structures is advancing. But, when a heavy section low alloy steel plate is welded, the weld metal toughness deteriorates. Therefore, it is very important to increase the weld metal toughness.

Then we have investigated the effects of the electron beam welding cooling rate and PWHT conditions on weld metal toughness and we have also studied the mechanism of toughness changes metallographically. Consequently, it has been clarified that in order to increase the toughness of electron beam weld metal for low alloy steel, the structure should be lower bainite by increasing welding cooling rate and a temper parameter of about 19 should be selected as the key for PWHT.

KEY WORDS: (Electron Beam Welding) (Low Alloy Steel) (Weld Metal Toughness) (Welding Cooling Rate) (PWHT Conditions) (Carbide Precipitation)

1. Introduction

When a heavy section low alloy steel plate is welded, the weld metal toughness deteriorates. Therefore, in order to apply electron beam welding to heavy section low alloy steel, it is important to increase the weld metal toughness.

Bonnin et al. reported that in electron beam welding the target toughness can be secured for plates 100mm thick or less, but toughness decreases for plates 120mm thick or more and so electron beam welding cannot be applied.1)

In general, PWHT (Post Weld Heat Treatment) is applied to the pressure vessels. It is known that the weld metal toughness of low alloy steel or high tensile strength steel changes from the as weld condition due to this PWHT.2,3)

In addition, the weld metal structure changes in the order of martensite, and lower bainite and also upper bainite with decreasing welding cooling rate. The lower bainite structure has the highest toughness and the upper bainite structure has the lowest toughness. Therefore, in order to improve toughness, the welding cooling rate should be increased.

Then, with low alloy steel plates 20mm and 120mm thick we have clarified the effects of the electron beam welding cooling rate and the PWHT conditions on weld metal toughness and we have also studied the mechanism of these toughness changes metallographically.

2. Materials and Experimental Method

SQV 2B is a commonly used low alloy steel in the pressure vessels of nuclear power plants. This steel is a type of Mn-Mo-Ni steel and is excellent in low temperature toughness and weldability.

SQV 2B steel plates of 20 and 120mm thickness were prepared as shown in Table 1 and experiments were carried out with them.

<table>
<thead>
<tr>
<th>Steel</th>
<th>Thickness (mm)</th>
<th>Chemical Compositions (wt%)</th>
<th>Mechanical Properties</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>C</td>
<td>Si</td>
<td>Mn</td>
</tr>
<tr>
<td>SQV2B</td>
<td>20</td>
<td>0.16</td>
<td>0.20</td>
</tr>
<tr>
<td></td>
<td>120</td>
<td>0.16</td>
<td>0.20</td>
</tr>
</tbody>
</table>

† Received on July 30, 1993
* Professor
** Associate Professor, Technical University of Košice (formerly the foreign researcher of JWRI)
*** Mitsubishi Heavy Industries, Ltd.

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<table>
<thead>
<tr>
<th>Table 2</th>
<th>Welding conditions</th>
</tr>
</thead>
<tbody>
<tr>
<td>Plate Thickness (mm)</td>
<td>Welding position</td>
</tr>
<tr>
<td>20</td>
<td>Horizontal</td>
</tr>
<tr>
<td>120</td>
<td>Horizontal</td>
</tr>
<tr>
<td>120</td>
<td>Horizontal</td>
</tr>
</tbody>
</table>

Electron beam welding was carried out in a full vacuum chamber. The electron gun used in the experiments had a capacity of 150kV in maximum accelerating voltage and 150kW in maximum power.

Bead on plate electron beam welding was carried out under the conditions shown in Table 2. Normal suitable welding conditions were applied to plates 20mm thick. For plates 120mm thick, the welding was carried out under both suitable welding heat input conditions and higher than suitable conditions in order to change the welding cooling rate.

In order to investigate the effect of PWHT conditions on toughness, with a temperature range of 868 to 923K and a holding time range of 9 to 72ks PWHT was carried out under the conditions shown in Table 3.

After PWHT, Charpy impact test pieces were cut out from the 1/2t section in plate thickness to investigate the toughness. In addition, we investigated the hardness, the microstructure and the continuous cooling transformation diagram. Besides we investigated the toughness changing mechanism by electron microscope observation of weld metal.

3. Electron Beam Welding Cooling Rate and the Welding CCT Diagram

3.1 Electron beam welding cooling rate

Electron beam welding is a two-dimensional heat flow (linear heat source), when viewed as a heat source. Therefore, when neglecting thermal radiation from surfaces, the welding cooling rate is equal for both thin and thick plates, ideally. However, in practice, the plate thickness that can be penetrated has a limit, depending on the capacity of the electron gun used. In general, with increasing plate thickness the welding heat input increases gradually and as the penetration limit is approached, the welding heat input increases rapidly.

In the two-dimensional heat flow the cooling rate at the welding center line is as shown by Eq.(1).^4

\[
C.R. = 2\pi \lambda C \rho \frac{v h}{Q} \cdot (\theta - \theta_0) \tag{1}
\]

where, \(\lambda\): Heat conductivity, \(C\): Specific heat, \(\rho\): Density, \(v\): Welding speed, \(h\): Plate thickness, \(Q\): Heat input, \(\theta\): Temperature, \(\theta_0\): Initial temperature

\[\text{Temp parameter} = T \times (20 - \log l) \times 10^{-3}\]

That is to say, the cooling rate is proportional to \((v h/Q)^2\). \((v h/Q)\) is equivalent to the welding heat input per unit plate thickness and it increases with increasing plate thickness.

Electron beam welding of the thick plate is carried out in the horizontal position to prevent molten pool from dropping down. In this case the electron beam penetrates through the welded plate to its back side, and the actual heat input to the welded plate is the electron gun output minus the penetrating beam power and energy from the reflection from the surfaces.

Therefore, the cooling rate is to be calculated by Eq.(1) with the corrected welding heat input. However, a method to estimate the cooling rate with the bead width and the heat affected zone width is also reported. It is natural that the bead width and the heat affected zone width change for the same electron gun, depending on the heat input. Thus, it is considered that these widths correspond to the cooling rate.

Kosuge et al. reported that cooling times form 1073K to 773K in electron beam welding for carbon steel can be estimated with Eq.(2).^5 Ohara et al. reported that they can be estimated with Eq.(3).

\[
\Delta t_{(773-773)} = 0.75 \times \text{(Bead width at the middle of plate thickness)}^2 \tag{2}
\]

\[
\Delta t_{(773-773)} = 1.107 \times \text{(Bead width at the middle of plate thickness)}^2 \tag{3}
\]

When the welding was carried out under the welding conditions shown in Table 2, the bead widths were about 3mm for plates 20mm thick, about 4mm for plates 120mm thick under suitable welding conditions, and about 6mm for plates 120mm thick under higher than suitable welding conditions. According to Eq.(2) cooling times from 1073K to 773K are 9s for plates 20mm thick, and 17s and 42s for plates 120mm thick. According to Eq.(3), they are 10s for plates 20mm thick, and 18s and 40s for plates 120mm thick.

Therefore, the cooling times are estimated to be about 10s for plates 20mm thick, about 20s for plates...
3.2 Welding CCT diagram for SQV 2B steel

We have prepared a welding CCT diagram as a reference to estimate the weld metal structure. 20mm thick material was selected for experiments from among steel plates shown in Table 1.

For the CCT curves the transformation measurement equipment (Formaster EDP) was used for measurement. The maximum heating temperature in the heating cycle was to be 1573K (cooling curve is straight) and the cooling rate was changed by 0.03 to 150K/s.

The obtained CCT diagram is shown in Fig.1. For a cooling rate of 10K/s or more, the microstructure is mainly a martensite structure and the hardness is Hv 394 to 427. On the other hand, for a cooling rate of 10 to 6K/s, the microstructure is martensite plus lower bainite and the hardness is Hv 365 to 398 respectively. For a rate of 3K/s or less, the microstructure is mainly upper bainite and the hardness is as low as Hv 223 to 305.

In electron beam welding the cooling rate from 1073 to 773K is about 10 to 40s and the cooling rate in this temperature range is estimated to be about 30 to 7.5K/s. It is estimated that the maximum peak temperature of the weld metal is higher than that of the welding CCT diagram, and the weld metal structure is mainly martensite for a thin plate of low welding heat input but mainly bainite for a thick plate of high heat input.

4. Effect of PWHT Conditions on Charpy Absorbed Energy

Investigated examples of the Charpy absorbed energy of SQV 2B steel are shown in Fig.2. In this test, electron beam welding was carried out with SQV 2B steel plates 90mm thick and then PWHT was carried out at 888K and 14.4ks. Charpy impact tests were carried out with notches positioned at the weld metal, the weld bond, the heat affected zone, and the base metal. The Charpy absorbed energies are in ascending order: the heat affected zone, the base metal, the weld bond and the weld metal. Toughness does not decrease especially in the weld bond and it is a medium value between those of the weld metal and the heat affected zone at the weld bond. The heat affected zone has a toughness better than that of the base metal.

Consequently, since it was judged important to secure toughness of the weld metal for the electron beam welded joint of SQV 2B steel, we carried out tests on the weld metal.

After manufacturing electron beam welded joints and carrying out the specified PWHT, fifteen pieces of Charpy impact test pieces were cut out from the plate middle sections. Then, the Charpy impact tests were carried out at five temperature levels to obtain the fracture appearance transition temperature. Table 4 shows the mean Charpy absorbed energy values (for values at 173 and 253K) and the fracture appearance transition temperature obtained in the Charpy impact tests.

![Fig.2 Charpy impact test results of ordinary SQV 2B steel](image-url)
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Table 4  Charpy impact test results

<table>
<thead>
<tr>
<th>Post weld heat treatment</th>
<th>Thickness 20mm</th>
<th>Thickness : 120mm</th>
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</thead>
<tbody>
<tr>
<td></td>
<td>vTrs (K)</td>
<td>vE₁₁₇₃ (J)</td>
</tr>
<tr>
<td>Temp. (K)</td>
<td>Time (ks)</td>
<td>Temp. parameter</td>
</tr>
<tr>
<td>923</td>
<td>72</td>
<td>19.7</td>
</tr>
<tr>
<td>923</td>
<td>27</td>
<td>19.3</td>
</tr>
<tr>
<td>923</td>
<td>9</td>
<td>18.8</td>
</tr>
<tr>
<td>908</td>
<td>9</td>
<td>18.5</td>
</tr>
<tr>
<td>893</td>
<td>36</td>
<td>18.8</td>
</tr>
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<td>893</td>
<td>9</td>
<td>18.2</td>
</tr>
<tr>
<td>868</td>
<td>9</td>
<td>17.7</td>
</tr>
<tr>
<td>As Weld</td>
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</tr>
</tbody>
</table>

Fig.3  Effect of temper parameter on vE₂₃₅ of weld metal

Fig.4  Effect of temper parameter on vE₁₁₇₃ of weld metal

Fig.5  Effect of temper parameter on vTrs of weld metal

The PWHT conditions were converted to a temper parameter to arrange the Charpy impact test results. Here, we used \(7 \times (20 + \log t) \times 10^{-3}\) as the temper parameter \(T\): Holding temperature (K) and \(t\): Holding time (hr).

Figure 3 shows the relationship between the Charpy absorbed energy and the temper parameter at 253K, Fig.4 shows it at 173K, and Fig.5 shows it between the fracture appearance transition temperature and the temper parameter in the Charpy impact tests. Figure 6 shows the fracture appearance transition temperature arranged from the viewpoint of the cooling rate in electron beam welding. With these figures, the following can be understood:

1. The cooling rate in electron beam welding has a large effect on the Charpy absorbed energy, and the higher the cooling rate is, the better the toughness is.

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That is to say, the fracture appearance transition temperature in the Charpy impact tests after optimum PWHT is about 133K for plates 20mm thick (bead width: about 3mm and cooling time from 1073 to 773K: about 10s), but it is 228K for plates 120mm thick and suitable welding heat input (bead width: about 4mm and cooling time from 1073 to 773K: about 20s) and it is 253K for plates 120mm and higher than suitable heat input (bead width: about 6mm and cooling time from 1073 to 773K: about 40s). These show that with the higher welding heat input and accordingly the lower welding cooling rate toughness decreases by a great amount. Besides, in as weld conditions also the fracture appearance transition temperatures are in increasing order of cooling rate, i.e. 173, 313 and 338K. The toughness as weld condition is inferior to the toughness when PWHT is applied, but the effect of the cooling rate is evident.

(2) The toughness is improved by PWHT. However, the larger temper parameter means no more improvable or lower toughness, and there is an optimum temper parameter range for obtaining good toughness.

Under all applied welding cooling rate conditions, the toughness becomes better up to about 19 in temper parameter. However, the toughness tends to decrease above 19.

Besides, even at a lower cooling rate for plates 120mm thick, toughness is improved greatly by PWHT, compared with the as weld conditions.

With these results, it can be clarified that the welding cooling rate and the PWHT conditions have a large effect on the toughness of electron beam welded joints of SQV 2B steel.

5. Metallographic Study of Electron Beam Weld Metal Structures

From the Charpy impact test results it is clear that the Charpy absorbed energy changes depending on PWHT conditions. Thus, we carried out a metallographic study to investigate these conditions; i.e. as weld conditions, a temper parameter of 18.8 (the key condition for peak toughness) and that of 19.7 (the key condition for low toughness).

Microstructure observation results obtained with an optical microscope and a scanning electron microscope (SEM) are shown in Figs. 7 and 8. The as weld structures are lower bainite for steel plates 20mm thick and upper
bainite for steel plates 120mm under both suitable welding conditions and higher than suitable welding heat input conditions. The microstructures in the weld metal are uniform and the primary austenite grains become smaller with decreasing heat input. In the optical microphotographs discontinuous black lines appear due to the PWHT and they are seen clearly in the cellular dendrite state of solidification in structure as the temper parameter becomes larger. These black lines are precipitated carbides from TEM results. With the higher welding heat input, this precipitation starts at the smaller temper parameter. The carbides precipitate along the cellular dendrite boundaries in great quantity. In the cellular dendrite boundaries Mn, Mo, etc. segregate.

According to the Ostwald theory, growth of the carbides is said to be affected by temperature, time, the distribution coefficients (K) of alloy elements to carbides and ferrite, etc., and the element of large K delays the growth of carbides. It is reported that the K at 973K are 10.5 for Mn, 28 for Cr, and 7.5 for Mo, and so it can be understood that Mn and Mo promote the growth of carbides. Figure 9 shows the observation results of the state where carbides precipitate nonuniformly on a Charpy impact fracture surface.

Element analysis results by EDX analysis are shown in Table 5. In round carbides Mo and Mn increase and a slight Cr increase is also seen. Regions rich in carbides are rich in Mn and Mo.

Figure 10 shows TEM (transmission electron microscope) observation results with carbon extraction replicas. In this TEM observation of the as weld state with a carbon extraction replica, it is known that there exists fine cementite particles of needle or round shapes among the laths. Cementite is to be spheroidized by tempering, but locally is not spheroidized fully even with a temper parameter of 18.8. With a parameter of 19.7 it is understood that the cementite particles become coarser. That is to say, cementite particle distribution with a parameter of 18.8 is more uniform than with that of 19.7. The cementite particles are alloy carbides.

Figure 11 shows TEM observation results with thin foils. In the optical microscope observation there is no difference in microstructure due to the difference in PWHT except carbide precipitation. However, there is a large difference in TEM observation with thin foils. That is to say, the as weld state is the state of laths have a high dislocation density, but PWHT brings this to a recovery stage. Complete recovery has been attained with a temper parameter of 18.8. And slender subgrains pin-connected by carbides have been uniform. An initial lath tendency remains and the dislocation density is lower than that for the as weld state, but there still

<table>
<thead>
<tr>
<th>Element</th>
<th>Mean particle size (nm)</th>
<th>Mean size (nm)</th>
<th>Mean size (nm)</th>
<th>Mean size (nm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cr</td>
<td>1.8</td>
<td>0.3</td>
<td>0.6</td>
<td>0.7</td>
</tr>
<tr>
<td>Mn</td>
<td>2.4</td>
<td>0.7</td>
<td>0.9</td>
<td>0.8</td>
</tr>
<tr>
<td>Fe</td>
<td>3.6</td>
<td>0.9</td>
<td>1.2</td>
<td>1.1</td>
</tr>
<tr>
<td>Ni</td>
<td>4.2</td>
<td>1.0</td>
<td>1.5</td>
<td>1.4</td>
</tr>
<tr>
<td>Mo</td>
<td>5.1</td>
<td>1.2</td>
<td>1.8</td>
<td>1.6</td>
</tr>
</tbody>
</table>
is dislocation in the subgrains. When the temper parameter becomes 19.7, further changes can be seen. In this state not only recovery but also the initial stage of recrystallization appears. The substructure becomes nonuniform because of combination of the recovered subgrains.

Figure 12 shows the SEM observation results of fracture surfaces in Charpy impact tests. With a temper parameter of 18.8 it is shown that the cleavage region is composed of fine crystal grains. On the other hand, with a temper parameter of 19.7, there appears nonuniformity in fracture facets and in large fracture facets corresponding to the recrystallization areas seen locally.

When changes of the carbide precipitation state due to PWHT are shown with a model, Fig.13 is obtained. In the as weld state uniformly-distributed fine carbides precipitate near subgrain boundaries due to tempering. As tempering proceeds further, large carbides precipitate in the subgrain boundaries and so carbides disappear in the neighboring regions. Then, in these regions recrystallization occurs.

Figure 14 shows the relationship between hardness and PWHT. PWHT decreases hardness fully and even by increasing the temper parameter the degree of the decrease is low.

Thus the causes of toughness change due to PWHT are considered to be as described in the following section. In the as weld state the dislocation density is high,
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As Weld

- Homogeneous carbide

PWHT 923K – 9ks

- Carbide precipitation near subgrain boundary

PWHT 923K – 72ks

- Carbide precipitation on subgrain boundary
- Carbide free area occurs near subgrain boundary

Fig.13 Change of carbide precipitation according to PWHT

SQV 2B Steel
Position: Electron beam weld metal, 1/2 t

Fig.14 Effect of temper parameter on Vickers hardness of weld metal

- Strength is also high, and so toughness is low. However, due to PWHT, the subgrains recover, and so toughness increases. On the other hand, as the temper parameter becomes larger, precipitation of carbides proceeds and also subgrain grows during recrystallization to produce regions having no carbide. Therefore, toughness decreases.

6. Conclusion

For the SQV 2B steel, we have clarified the effect of welding cooling rate and PWHT conditions on the toughness of electron beam weld metal of low alloy steel, and also carried out an electron microscope observation of the effect of the microstructure on toughness. The obtained results are summarized as follows:

1. For SQV 2B steel, weld metal structure changes depend on plate thickness. This affects the lower bainite structure for plates 20mm thick and the upper bainite structure for plates 120mm thick because of the lower welding cooling rate.

2. The Charpy impact characteristic of the weld metal is affected by the microstructure. The fracture appearance transition temperatures for the as weld state are 173K for plates 20mm thick, 313K for plates of 120mm thick and suitable welding heat input, and 338K for plates 120mm thick and higher than suitable welding heat input.

3. Toughness is improved by applying PWHT. Fracture appearance transition temperatures after optimum PWHT are 133K for plates 20mm thick, 228K for plates 120mm thick and suitable welding heat input and 253K for plates 120mm thick and higher than suitable welding heat input. Compared with the value for the as weld state, a remarkable improvement is seen, i.e. 40K for plates 20mm thick and 85K for plates 120mm thick.

4. With a temper parameter of up to about 19, toughness is improved, but toughness decreases above 19. Toughness increases because the structure recovers due to tempering. However, when the temper parameter is above 19, an initial recrystallization stage appears. This recrystallization area, because it has no carbide, generates large fracture facets in the Charpy impact test, and so toughness decreases.

5. From the above findings it has been clarified that in order to increase the toughness of electron beam weld metal for low alloy steel the structure should be lower bainite the weld bead width should be narrow and the welding cooling rate should be increased, and a temper parameter of about 19 should be selected as the key PWHT.

References